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HYDROGEN AIRCRAFT AND AIRPORT SAFETY

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Abstract—Hydrogen will be used as aviation fuel in the foreseeable future. First flight tests with a hydrogen demonstrator aircraft, currently under investigation in the scope of the German–Russian Cryoplane project, are scheduled for 1999. Regular service with regional aircraft may begin around 2005, followed by larger Airbus-type airliners around 2010–2015. The fuel storage aboard such airliners will be of the order of 15 t or roughly 200 m^3 LH_2. This paper investigates a number of safety problems associated with the handling and air transport of so much hydrogen. The same is done for the infrastructure on the airport. Major risks are identified, and appropriate measures in design and operation are recommended. It is found that hydrogen aircraft are no more dangerous than conventional ones—safer in some respects. Many risks can be avoided by suitable constructive measures, and the rest are bearable. The real challenge lies with the dimensions of the installations on the airfields which will become necessary when hydrogen aircraft become common.

1. INTRODUCTION

1.1. *Why we need hydrogen*

The introduction of hydrogen technology is much more than just a technical transition to a more economical or practical fuel. Conventional fossil fuels will soon no longer be available in sufficient amounts because of the exhaustion of resources. This problem becomes more and more evident due to the growth of the world population and the rapid

industrial development of some of the most populated regions of the earth. An even more important aspect is that the consumption of conventional fuels damages the atmosphere locally (air pollution) and globally (greenhouse effect, ozone depletion). Even the use of all available means to save energy right now could not turn the trend fundamentally. This is a danger to the whole earth.

Hydrogen is the most promising candidate for an alternative fuel in a new global energy system. It is available on earth in abundant supply, even though it must be separated from water or other chemical compounds before use. The environmental effect associated with its combustion or other use is negligible. Even in case of an accident it is less dangerous than conventional hydro-carbon fuels.

1.2. *Why aviation needs hydrogen*

The necessary steps towards hydrogen technology must also be carried out in aviation, even though air transport may be a luxury for large parts of the world population and the absolute impact of aviation on the environment is smaller than that of surface transport. For the economy of the industrialized world, however, air transport plays a key role. Per passenger and mile, air transport causes comparably high environmental impacts, since pollutants are emitted in very sensitive layers of the atmosphere [1]. Moreover, local air pollution around major airports cannot be neglected.

This is why the aviation industry must also be prepared for the introduction of hydrogen fuel. The Cryoplane project is carried out with this background in mind.

2. THE CRYOPLANE PROJECT

2.1. *Objective*

Cryoplane is a joint project by Daimler-Benz Aerospace Airbus (Germany) and Tupolev (Russia) as well as a number of other partners. The objective is to develop commercial aircraft using liquefied natural gas (LNG) or liquid hydrogen (LH_2) instead of kerosene.

Important work to this end was done by Tupolev in the 1980s. A lot of experience has been gathered by developing and operating a flying laboratory called Tu-155 which first flew in 1988. The results will be used for the Cryoplane project.

As a first step towards cryogenic fuel aircraft, the modification of conventional commercial transport is considered. The modifications will mainly affect fuel storage and engines. Later generations of aircraft will have to be adapted to the particular characteristics of cryogenic fuels, above all the comparably high volume requirements which may lead to configurations much different from those of kerosene aircraft. An example is shown in Figs 1–3 featuring two cylindrical LH_2 tanks mounted above the wings and connected to the horizontal tail.

2.2. *Economical considerations*

The product cycles of commercial aircraft are of the order of 50 years (from the start of development to the phasing out of the last serial aircraft). The first large Cryoplane aircraft may enter into service in the time frame 2010–2015 [2, 3].

Fuel prices will undergo dramatic changes until then. Kerosene and other hydrocarbon fuels will become more expensive due to the exhaustion of the reserves and possibly due to environmental taxation, while the price of hydrogen will drop due to improved supply (see

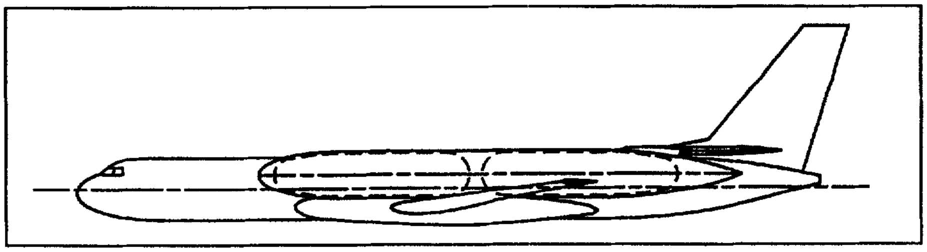

Fig. 1. Design study of an LH_2 aircraft (reproduced with kind permission of Tupolev Aviation Corporation, Moscow), side view.

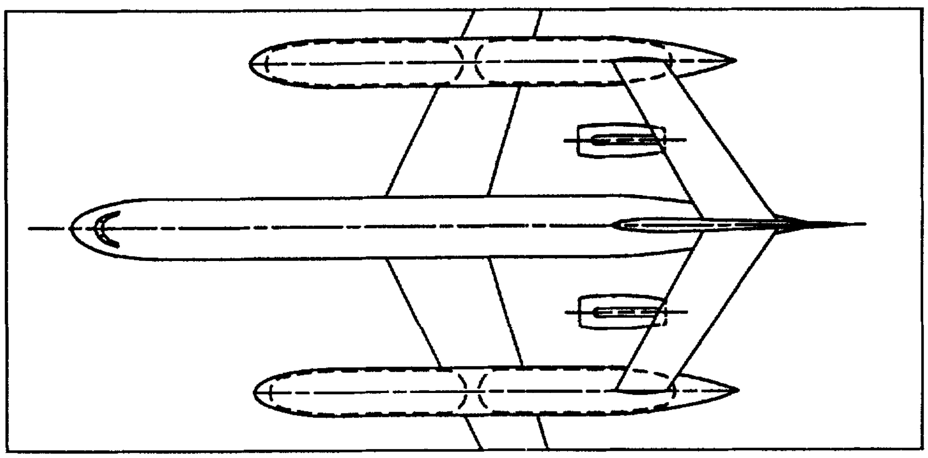

Fig. 2. Design study of an LH_2 aircraft, top view.

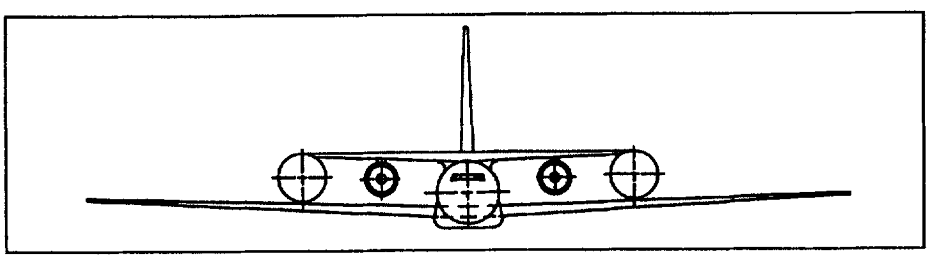

Fig. 3. Design study of an LH_2 aircraft, front view.

Fig. 4). This alone is a compelling reason for starting the development of alternatives now, apart from all the ecological considerations.

The accuracy of such forecasts depends always on global political and economical developments which are difficult to predict. The introduction of the nuclear aircraft and of the 1000 passenger Jumbo were announced in the 1960s for the mid-1980s [4]. The interest

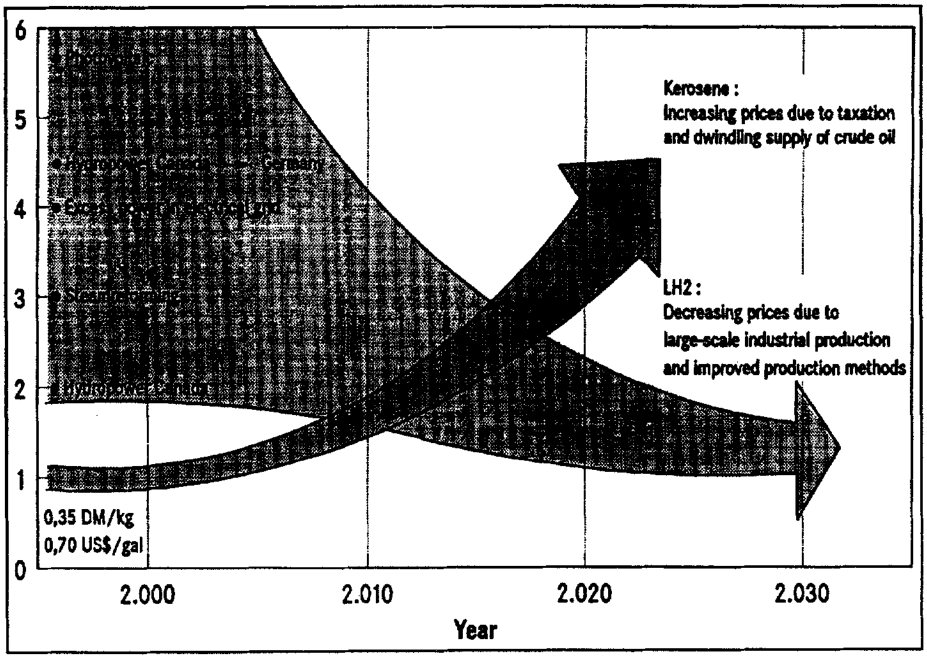

Fig. 4. Kerosene and LH_2 price trend to be expected during the Cryoplane life cycle.

in hydrogen aircraft and hydrogen technology, however, has deeper roots than just the technical or business progress; political and economical boundary conditions may delay it, but are not likely to stop it.

3. RISKS ASSOCIATED WITH HYDROGEN

3.1. *Physical properties*

The selection of LH_2 fuel will provide a safety advantage to hydrogen aircraft and airports in certain respects, because many safety problems associated with oil or products refined from it do not exist at all. In contrast to conventional liquid fuels hydrogen is a gas that cannot seep into the ground and contaminate soil and water. Such things happened with kerosene for years on some airports (e.g. Frankfurt Airbase) without anybody noticing it.

The storage of hydrogen as cryogenic liquid is in certain respects safer than storing it as compressed gas, because the lower pressure reduces the mechanical loads on the tank and thus, the problem of material fatigue. An accident of the Hanau type, the characteristic feature of which was early material fatigue due to cyclic tensions under the influence of compressed hydrogen at ambient temperature, would be most unlikely in connection with liquid hydrogen, because the pressures are generally lower and do not vary cyclically with consumption or tank fill ratio to the same extent [5, 6]. The designer of hydrogen tanks or devices must, however, consider that hydrogen at the same time favours fatigue and embrittlement of certain materials [5]. This is an effect not of the hydrogen molecule, but of the atom, and happens faster when the pressure is higher.

The low temperature of LH_2 may make handling more complicated and thus sensitive to problems. There might be an insulating vacuum as an additional component which can cause difficulties of its own. Also to be considered are the effects of the low temperature on the materials in contact with the cryogen. Characteristic properties will change, and organic or other elastic materials in particular become brittle.

Another problem is related to the small size of the hydrogen molecule. It can pass through narrow openings more easily than air or other comparable gases, which means that the measurement of a leak rate with air will give misleading results. Hydrogen can even enter solid materials by means of permeation, in particular polymers. While it can be shown that this effect is not important at 20 K, there are always warm parts in any construction, therefore materials should be chosen carefully [7, 8].

3.2. *Chemical properties*

The only major chemical risk associated with hydrogen under ambient conditions is its flammability. This is, of course, common to all fuels. Gaseous hydrogen can also mix with air and form flammable and explosive mixtures more easily than kerosene vapours.

The heat radiation of a hydrogen flame is only about 10 % of that of a hydrocarbon flame, which means that the site of a hydrogen fire is more easily accessible for rescue forces than a hydrocarbon fuel fire.

These properties do not depend on whether hydrogen is stored as gas or cryogenic liquid.

3.3. *Physiological properties*

Hydrogen is neither poisonous nor corrosive. It may, of course, be asphyxiating if it is present in such an amount that not enough oxygen is left for breathing. Spilled hydrogen pollutes neither surface or ground water, nor the soil.

The low temperature of LH_2 may have physiological effects in case of release; while the liquid itself will usually not hurt the skin due to the vapour cushion between the cold liquid and the warm skin ("Leidenfrost effect"), injuries comparable to burning may occur when cold metal parts are touched.

3.4. *Facts and fiction*

While most experts agree that the risks associated with hydrogen are even smaller than in case of conventional fuels [9] (not even considering the ecological balance), the public have a quite different opinion. There are widespread misgivings about the use of hydrogen for any purpose. This is commonly known as the "Hindenburg Syndrome", referring to the most spectacular hydrogen accident.

The main reason for this hydrogen fear is that the public is not used to hydrogen in contrast to oil products, and while spectacular hydrogen accidents like that of the "Hindenburg" remain in memory for decades, people get used to severe car crashes and oil spills. The success of hydrogen technology depends, therefore, not only on suitable technical provisions but also on skilful and honest public relations work.

3.5. *Objective of this study*

The high public safety demands on technical installations of any kind, the high safety standards which exist in aviation anyway, and the special technical and psychological problems associated with hydrogen are the basis for a particular necessity of safety related research in connection with projects like the Cryoplane.

This study will identify the most likely and hazardous emergency situations in the operation of a hydrogen aircraft and propose suitable countermeasures. Most of the danger is related to the uncontrolled release and dispersion of ignitable gas mixtures. An explosion at an airport would affect many people and cause high damage. It would be even more dangerous on board an aeroplane, because countermeasures during flight are limited, and it is not possible to walk away from the danger. This is why both airport and aircraft are the object of this study.

4. STATE OF THE ART

4.1. *General*

The existence of hydrogen has been known for 200 years, and its properties have been studied extensively, including those of the condensed phases. Also known are the relevant safety properties of hydrogen in comparison with natural gas, petroleum gases, common jet fuel, car fuel, and similar substances. Comparisons can be found in [9] and many other sources.

4.2. *Hydrogen aircraft*

The role of hydrogen in aviation was originally to provide buoyancy for balloons and airships. The only large scale application of hydrogen as fuel is for spacecraft. All other work in this field was experimental in nature.

The first prototype of a hydrogen aircraft flew in 1956. It was a modified B57 bomber running on liquid hydrogen (LH_2). Various fuel supply systems were investigated [10].

The latest example is Tupolev's "flying laboratory" Tu-155 mentioned above. It is a modified commercial aircraft on the basis of the successful type Tu-154, with the right engine modified in such a way that it can be run on kerosene, LNG, or LH_2. Experiments have been carried out since 1988, and the results will have an effect on Cryoplane [11].

4.3. *Supply and infrastructure*

The infrastructure for hydrogen aircraft was investigated in two studies made for NASA in the 1970s. Necessary installations for the supply and the related investments were identified on the basis of the conditions for the airports of San Francisco [12] and Chicago [13]. Safety matters were dealt with in these studies, but not primarily. A similar study with the focus on economics was made in the 1980s for Zurich airport [14].

4.4. *General hydrogen safety*

There are investigations on hydrogen related safety matters for aerospace purposes which will be dealt with below. There is, however, also experience relevant to aviation which has been gathered outside the aerospace industry.

The technically most advanced project for the demonstration of production, transport, storage, and use of LH_2 fuel is the "Euro-Québec Hydro-Hydrogen Pilot Project" (EQHHPP) [15, 16] which is a joint activity of the European Union and the Canadian province of Québec. LH_2 will be transported by means of a special ship from Québec to Hamburg to be used in various model applications. Some valuable specific safety-related work has been done in this context. In addition there have been studies from Canada about the likely effects of large scale LH_2 use for advanced technologies [17]. Another EQHHPP study by the Research Center Jülich (Germany) deals with the probability of LH_2 ship

accidents on the Elbe river and their effects together with cryogenic pool behaviour [18]; the results can be compared with those for LNG ships [19].

In May 1994 the Federal Institute for Materials Research and Testing (BAM) carried out experiments on the dispersion behaviour of hydrogen/air clouds in the framework of the EQHHPP [20, 21]. These tests were made between houses to get a surrounding similar to an actual accident site. Comparative tests were made with LPG (i.e. Liquefied Petroleum Gases, in particular propane). Ignition experiments with such clouds will be made later.

The nuclear industry has an interest of its own in hydrogen safety. In 1991 the Research Center Jülich carried out experiments [22] with balloons containing approximately 50 m^3 of hydrogen/air mixture that were ignited by means of an explosive detonator. The mixture ratio was either stoichiometric or just above the lower detonation limit. The objective was to gather knowledge about the detonation of such mixtures and about the deflagration/detonation transition process.

Accident simulation is valuable, but the cause and mechanism of real accidents must also be investigated. One important example from the more recent past is the gas tank accident which happened at Hanau (Germany) [5]. There are also compilations of different types of hydrogen accident with statistical data covering cause and effect [6].

4.5. *Aerospace safety*

There are numerous investigations and handbooks on aviation safety generally. In one of them [23] estimations of the effects of fuel explosions (pressure waves, debris impact) can be found.

Most studies about the particular matter of hydrogen safety were related to the US space program. Some of them simulated hydrogen accidents and observed the effects. Many of them are no longer new, but still the standard. There has been a marked decrease of these activities since the end of the Apollo program in the mid-1970s. Similar investigations were made in the U.S.S.R., but are not so widely published.

There are not many aerospace investigations with the special attention to hydrogen safety. General studies and compilations are for example [24] or [25]. Some particular publications should be mentioned here.

- Lockheed investigated the detonation risk associated with hydrogen/air mixtures (this was done in connection with the work on the hydrogen aircraft prototype). Release and vaporization of LH_2 were assumed as source of the mixture. The results have not been published widely because the whole program was aborted [26].
- Much better known are the Arthur D. Little experiments [27]. Various amounts of LH_2 were spilled in an open area, and the mixture dispersion and other effects were observed. Comparative experiments with conventional fuels and ignitions were made.
- More systematic and greater experiments of this kind were made by NASA [28, 29]. The results have the same direction.

These and previous studies, as well as our own experience, were evaluated by Airbus for the Cryoplane project [11].

4.6. *Regulations*

There are regulations for potentially dangerous plants and devices in every individual country, and there are also regional rules (e.g. those of the European Union) and international rules (e.g. those for the transport of dangerous goods). In Germany, pressure

vessels on the ground are subject to the Pressure Vessel Decree (Druckbehälterverordnung [30]) and its Technical Rules. Other applicable German rules are those concerning explosion protection [31], work sites [32] and commercial handling of dangerous chemical substances [33]. Of particular importance is the law regarding the protection of the environment (Bundes-Immissionsschutzgesetz [34]) with its various decrees, in particular the regulation concerning emergencies (Störfallverordnung). Air transport is not in the scope of some of these regulations, but a large part of their content can be found in specifically applicable rules. While other countries have different regulations, they are being continuously harmonized at least between the member states of the European Union, as a result of the progress in the creation of a single interior market.

There are also comprehensive regulations for conventional aircraft and air transport, which deal with transport and environmental matters and also with safety. Liquid hydrogen is, not surprisingly, not considered by them. Technical safety and the protection of the public, however, are a key issue for the whole hydrogen technology. This means that not only more and new research, but also a parallel development of the regulations are necessary [35]. This holds not only for air transport, but generally for matters of transport, transfer, and storage of LH_2 [36, 37].

Regulations must have deficiencies because they can, by their very nature, best reflect the present technical knowledge; they cannot pioneer the way for new developments like Cryoplane. The experience collected in them, however, can and will be used whenever necessary or useful.

5. AIRPORT DESIGN

5.1. *State of the art*

No present airport has facilities for the supply of hydrogen aircraft because there are none in regular service. There are, however, investigations into what such facilities should look like [12–14]. The assumptions made here about the traffic at the airport will be basically the same as those made in the study for San Francisco [12]. The main points will be summarized below and compared with the more recent results of the Cryoplane proposals.

5.2. *Liquefaction*

While [12] proposes the delivery of gaseous hydrogen to a liquefaction plant at the airport, Cryoplane favours the production of hydrogen on the site by means of electrolysis.

Hydrogen liquefaction will be done at the airport site. The liquid will be distributed from there to the aircraft without further intermediate transport. The distribution of hydrogen liquefied elsewhere by means of tank cars or pipelines would be uneconomical, because of the high consumption of the airport. It would also cause additional and serious safety problems.

The supply of a plant of this type with dimensions discussed below with energy and raw materials is an important design problem, but not included in the scope of this study.

5.3. *Liquefier capacity*

While a hydrogen liquefier for an airport would in itself not differ much from any other plant of this kind, the specific environment must be considered.

The risk associated with a plant depends on the hydrogen inventory, which in turn depends on the demand to be expected. The daily demand varies, and must be taken into

account in the storage design. There are also seasonal variations with a demand peak in summer. The studies for San Francisco [12] and Chicago [13] came to the conclusion that an average daily demand of 800 t would be likely and recommended a plant design for 1000 t/d.

The estimations made for Cryoplane take into account the airport size distribution. The results vary between 40 t/d for a small German airport (e.g Bremen) and 4000 t/d for a major site (e.g. Frankfurt). Berlin's future airport would be somewhere in between with 1600 t/d [11]. The accuracy of such predictions may be affected by global developments; the importance of Berlin, for example, will depend on the economical progress in central and eastern Europe. Such internal variations, however, would have no effect on the global situations. This paper does not deal with the specific conditions of a particular airport.

5.4. *Considerations associated with the plant size*

Hydrogen liquefiers are state of the art, but the capacity under discussion is not. The most important plants in Western Europe are at Ingolstadt (Germany) [38], Rozenburg (near Rotterdam, The Netherlands) and Waziers (near Lille, France). The total production in Western Europe is about 20 t/d [38], which is less than the demand of even one small airport. The largest plants in the world have a capacity of about 30 t/d, while 250 t/d are considered as economical maximum [39]. The largest plants serve space centres (Florida/NASA, Kourou/ESA).

The energy demand of such a plant would also exceed present dimensions. The demand of the future airport of Berlin has been estimated to be roughly the same as the whole capacity of all power plants in former West Berlin (which was a city of 2 million inhabitants) [11].

Hydrogen aircraft can make sense commercially only if there is a sufficient number of airports with hydrogen facilities, otherwise they could operate between two or three places only. Figure 5 shows which airports would have to be suitably equipped if just wide-body

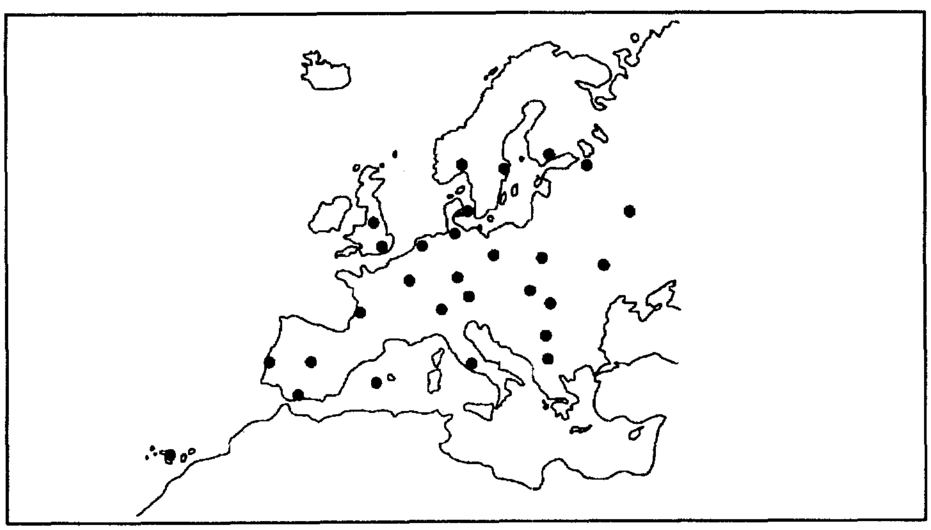

Fig. 5. Hydrogen airports in Europe, initial stage.

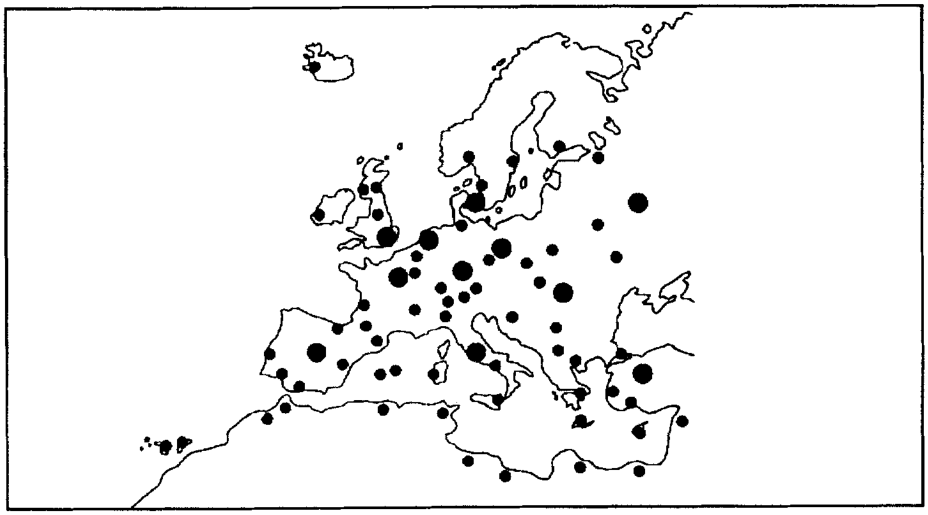

Fig. 6. Hydrogen airports in Europe, final stage.

aircraft in inner-European service were to use hydrogen. The corresponding pattern for the whole air transport into and from Europe is given in Fig. 6 [11]. Similar considerations can be made for North America or Eastern Asia. It is easy to recognize that this will require not so much a technical but rather an economical transition of major extent.

5.5. *Modular design*

There are technical and economical limits for the capacity of a hydrogen liquefier. The above mentioned limit of 250 t/d [39] is rather a theoretical value. Existing facilities are limited to 50 or 60 t/d because of the compressor capacity. Though one liquefier could, of course, be served by more than one compressor [11], the plant must have a modular design in any case. Cost and technical reasons favour a uniform design of the modules with a capacity of about 60 t/d.

Even for small airports three modules would be recommended to guarantee uninterrupted operation even if one module is out of operation for maintenance or some other reason. Larger airports must, of course, have more liquefier modules.

5.6. *Hydrogen storage*

Even though the customers of the liquefier are not far away, extensive storage facilities will be necessary, mainly for three reasons:

- a buffer volume should guarantee the supply even in times of peak demand;
- the liquid should be stored somewhere in case of low demand in order to avoid interruptions of the plant operation;
- flight operations should not be affected by plant failures.

While the liquefier should operate continuously, the demand varies considerably with time. It is very small between 22:00 and 06:00 on most airports. This means that the storage should at least accommodate the production of eight hours, while more is strongly recommendable.

The Cryoplane studies assume LH_2 storage tanks of 1700 m^3 (120 t) each [11]. Such a tank could serve four liquefier modules, so that the number of tanks per airport would be between one and fifteen. Even a small airport should have more than one tank, preferably three.

5.7. *Distribution*

The LH_2 fuel will be distributed by means of a vacuum insulated circular pipeline supplying various tank positions. The alternative of tank cars servicing the aircraft is inferior for safety, economical, and ecological reasons. Each additional transfer is a risk and associated with losses. At least some positions in the maintenance area must have the equipment for emptying full tanks and recovering the liquid.

For redundancy reasons it is recommendable to have a double LH_2 pipeline and a gas recovery line. Helium, nitrogen or other gases must be available for purging.

Pipelines like this are state of the art [40].

5.8. *Location of fuelling positions*

The aircraft will be refuelled at gate positions or near the terminals in parallel with cleaning, maintenance, and other work, as well as disembarking and boarding of the passengers, as is the case with today's kerosene aircraft.

Various other methods are discussed in [12]. Among these are special tank positions which are separated from the passenger area. The planes would have to return to the terminal for boarding, or the passengers would have to be shuttled to the aircraft by means of buses, or the passenger bridges would have to be much longer than at present. These alternatives have been rejected [12] mainly for economical reasons. The aircraft would have to stay at the airport much longer, which would mean a significant cost increase. No safety advantage is apparent.

Some tank positions should be available in the maintenance area for the servicing of aircraft which will not fly again in the near future. These, of course, should be duly separated from the passenger area and from the other flight operations.

5.9. *Other substances*

While hydrogen is the dominant dangerous substance in the liquefier, there are others as well. A hydrogen or helium liquefier needs considerable amounts of liquid nitrogen (LN_2). Another essential item is helium because it is the only substance which is still gaseous at 20 K. Also to be considered are electricity and other things necessary for the operation.

6. AIRPORT RISKS

6.1. *Legal aspects*

A hydrogen liquefier in Germany would have to be approved under environment legislation (Bundes-Immissionsschutzgesetz, Störfallverordnung [34]). Even though air transport facilities may not be completely included in the scope of [34], it would in any case be necessary under EU legislation to make a comprehensive study of the effects of the plant on the environment (UVPG [41]). Pressure vessels with their piping and equipment in Germany are subject to the pressure vessel legislation, though it has been shown elsewhere [36] that the rules are rather deficient for this application. The plant being commercial in nature, the rules for work sites [32] and dangerous substances [33] must be considered.

This paper is not intended for German readers only, however, even though in Germany the environmental legislation does not fully apply to air transport facilities, the approach demanded in [34] can be applied and this will be done here. *Legal requirements will be given in italics.* "Plant" comprises both the hydrogen liquefier and the Cryoplanes.

6.2. *Normal operation*

The effects of a plant on the environment should already be as low as possible during normal operation. Adverse effects to be considered are mainly noise and air pollution.

The liquefier is negligible in comparison to the air traffic in both regards. The main problem with the exhaust gases is the reduction of their NO_x content. First results of hydrogen combuster tests in the scope of the Euro–Québec Hydro-Hydrogen Pilot Project have indicated a NO_x reduction potential of up to 95 % as compared to conventional kerosene engines. Water vapour, according to recent investigations of climatologic institutions, has no significant atmospheric impact up to cruise altitudes of subsonic airliners. Water vapour on or near ground is legally not regarded as pollution because the air contains water anyway. All other emissions are negligible due to the use of hydrogen.

As far as the approval of the normal operation is concerned, an airport with hydrogen facilities might cause even less environmental and legal problems than a conventional one.

6.3. *Emergencies*

Plants have to be designed and operated in such a way that emergencies are avoided as far as possible. There is no uncommon risk associated to the operation of air separation plants and helium or hydrogen liquefiers, but they are a proven technology and have a high safety level.

Of course, even the safest plant will inevitably be affected by accidents. *Plant design and operation must therefore be such that accident effects remain on a low level, preferably inside the plant.* Airports already have a high level of technical safety, including fire brigade services. The measures necessary to be equipped for emergencies in the operation of hydrogen facilities like these should not be extraordinary.

6.4. *Effects of emergencies elsewhere*

Safety studies must include not only dangers arising in the plant itself. *Accidents in the vicinity of the plant should not have dangerous effects on it.* Such accidents will occur mainly in connection with the flight operations. They can cause fire and flying debris which could affect the liquefier. This risk shall be minimized by suitable choice of the location (off the direction of the approach paths), safety distances, protective mounds and so on. The plant should be as isolated as possible.

The liquefier and the rest of the airport shall also be protected against the effects of accidents outside the airport. Which accidents exactly are likely depends on the particular site. Such effects must be dealt with in the same way as those of accidents inside the airport.

6.5. *Trespassing*

Damage caused by unauthorized persons, whether committed maliciously or for other reasons, must be avoided by access restrictions. These restrictions must be enforced more strictly for the hydrogen facilities than anywhere else in the airport, even after the operation has become a routine. Access privileges should be differentiated and temporary.

7. PREVENTION OF AIRPORT ACCIDENTS

7.1. *Liquefier design*

Gas liquefaction plants are state of the art. What is necessary to make them run safely is already known [38], only the size is unusual. The capacity of all Western European plants together is one order of magnitude below the demand of one major airport, as mentioned earlier.

Special attention must be given to those components which must be developed for this application so that there is no experience from practical service. This applies in particular for LH_2 pumps. Pumps are recommended in [12] for thermodynamic reasons, and their use is also intended for Cryoplane. Their development, however, is not as advanced as would be desirable. An extensive and comprehensive test program, including all normal and abnormal situations, is necessary before they can be approved for service. Accessories and connections are known as weak points, because they are involved in about 44 % of the accidents [42].

The most dangerous situations are caused by human error. This can happen at the liquefier as well, even though a great part of the operation will run automatically. Since, however, the personnel are specially trained, the risk is comparatively low, provided the level of training and education is maintained. This applies in particular for emergency measures.

A principal potential risk of LH_2 is its low temperature. While direct contact of the skin with the liquid is unlikely, touching cold metallic parts should be avoided. If the temperature of the metallic parts which are in contact with air falls or may fall below 90 K, oxygen can condense on them. This is particularly dangerous if the liquid runs down a pipe or something similar and accumulates elsewhere. Pipes for cold gas should be thermally insulated. If the pipes are not very likely to become cold, a foam cover might do.

All unusual events, no matter how important, must be documented. This provides a valuable early warning system for weak spots of the plant which might cause serious damage one day if not dealt with properly.

7.2. *Passive protection of the liquefier*

The LH_2 liquefier and the storage must be located in such a way that there is optimum protection from the effects of accidents in other installations. Examples of the latter would be kerosene storage and air traffic. The liquefier must be located offside the runway centerlines.

Safety distances for the protection from accident effects elsewhere, and the protection of the surrounding area from accidents in the plant, are demanded anyway in the building regulations of most countries. The values given are usually derived from experience with LPG or other hydrocarbon gases. This means that they can be considered as conservative for hydrogen, because the danger that the gas may travel along the ground to distant ignition sources does not exist to the same extent for a hydrogen/air mixture than, for example, a propane/air mixture. This is an important difference from the point of view of safety engineering [20, 21, 43].

An additional safety possibility is the construction of earth or other mounds to protect the liquefier against flying debris, heat radiation or pressure waves. Such structures can also serve for access restriction.

7.3. *Storage tank design*

The tanks will almost certainly have double walls and vacuum insulation. Various alternatives, together with economical aspects are discussed in [12], but the result is the same.

The tank shape may be a vertical or horizontal cylinder or a sphere. The sphere has the smallest surface per unit volume, which reduces the heat load. There is a spherical NASA tank in Florida of 3000 m^3 LH_2. A sphere, however, is much more difficult to manufacture than a cylinder, especially if it is double-walled. The free liquid surface in a partially empty sphere is greater than in a vertical cylinder, which is thermodynamically disadvantageous. The heat load advantage of a spherical tank and the holding time will probably not be the key points anyway because the liquid is not stored for a long time. The cylinder tank will probably be preferable. There is no significant safety difference in the operation of both tank shapes; there is, however, a greater risk for production faults in case of a spherical tank because it is more complicated.

A cylindrical tank may be vertical or horizontal, which is no great safety difference either. Most large tanks for cryogenic liquids are vertical cylinders because of the smaller free surface of the liquid and the shorter line of contact with the wall. Both factors reduce the heat load. The final decision, however, must be made under consideration of the conditions on a particular site. While an upright cylinder may need more protection from flying fragments, it requires less ground area, which is an important boundary condition as well.

7.4. *Storage tank protection*

Risks for tanks containing flammable liquids or gases may be avoided by covering them with a layer of earth. This method is recommended in Germany for LPG tanks. Only the face or only the equipment of the tanks is left accessible. This is a good protection against heat radiation and impact of flying debris. For tanks with cryogenic content, however, the matter is not so easy because the earth around the tank would slowly, but certainly, freeze. Earth cover for the tank must, therefore, always be accompanied by additional measures which admit air to the tank walls.

Such schemes are discussed in [12], but are rejected. One reason is that the ground water on San Francisco airport is salty because the site is located directly at the coast. This incurs additional costs for corrosion protection. The main reason is economy, not safety.

Money spent for safety is, of course, principally a good investment when compared with the costs caused by mishaps and accidents. While ground water will be a problem anywhere, even if it is not salty, suitable materials and surface covers are known. Parts, equipment, and connections can be made such that no maintenance is necessary during the expected tank lifetime. The most important components and equipment should be accessible anyway.

An alternative, combining the advantages of earth cover with access to the tank, would be an open dugout with concrete walls such that only the top of the tank would be visible, but the tank walls would be accessible. Such a dugout would need a drain for rainwater if it is open, and it must be kept clean. Protection against the impact of great fragments from above (engines, wheels) could be provided by a suitable roof, if absolutely necessary. Such a roof should have openings for ventilation.

7.5. *Storage tank distribution*

The spatial distribution of the tanks must be decided on the basis of the specific conditions on the airport site. Certain safety distances are necessary from and between the tanks. The

distance to the liquefier must be an optimum between a great safety distance and small transfer losses. Other factors to be considered are the ground area available and the direction from which potential dangers might come.

It is not necessary to discuss the equipment of the tanks and of the whole plant in this context, because it is principally state of the art. The requirements for the supply of flight operations do not introduce anything basically new. A storage of the order of magnitude of 1700 m^3 is certainly not common, but larger storage facilities exist. Tanks of 3600 m^3 geometrical volume are planned for the Euro–Québec Hydro-Hydrogen Pilot Project (EQHHPP) [36], with the additional problem of suitability for sea transport.

7.6. *Operation*

The most possible dangerous situations are related to the failure of pipes, connections, or equipment and subsequent hydrogen release. The gas forms an easily ignitable mixture with air. Possible ignition sources must be minimized. Electrical installations must be explosion proof, metal structures must be grounded, and open fire (smoking) must be forbidden. Motor vehicles or comparable machines (including e.g. lawn cutters) must not operate in and around the plant or only under safety restrictions and conditions. All these rules follow from the usual regulations for work protection and prevention of accidents like, for example, in Germany [44].

Similar precautions must be taken to prevent the formation of an ignitable mixture inside a duct or tank.

7.7. *Fuel distribution line*

The hydrogen will be distributed by means of a long ring pipeline of which most parts will not be under continuous personal supervision. The risks associated with it are not the same as in the case of the liquefier.

It goes without saying that such a pipeline must be below ground level. If it is installed in a closed tunnel, a sufficient number of independent gas alarms is necessary. Damage to the liquid lines would soon be noticed because of the loss of the insulating vacuum.

The San Francisco study [12] proposed an open trench covered with grids. This would permit the escape of released hydrogen. The lines could be provided with a thin metal cover fitted with gas alarm on the inner side. The cover would not have to be tight or heavy, because it should be easy to open for maintenance. Valves and other equipment could also fit under this cover.

Care must be taken to avoid the accumulation of kerosene or other flammable material (leaves), rainwater or anything else in the trench. Ground contaminated by kerosene spills should not be able to pose a risk to the trench.

7.8. *Miscellaneous*

The plant and its periphery will have to be equipped with safety provisions similar to those for chemical plants or gas storage. Many requirements will be derived, at least analogously, from the regulations mentioned earlier applying to the latter. Even if not formally applicable, the content will be similar; it will certainly not be on a lower level.

Gas alarm devices and other alarms are important. Venting must be provided at places where hydrogen will or could escape. These precautions must be made according to the state of the art and not necessarily only according to the regulations.

Grounding of plant parts wherever necessary is an essential safety precaution. This

applies not only to the liquefaction plant, but even more to the planes whose charge depends on flight and landing history. Grounding must, therefore, be a basic requirement for tank and maintenance procedures.

A well organized control and maintenance schedule is a very good measure against plant failures and accidents, provided care is taken to follow it.

8. AIRPORT EMERGENCY MEASURES

8.1. *General*

There is a high safety level on an airport anyway, from which hydrogen facilities will profit. There is, for example, a fire brigade which would have to be trained for the dangers associated with hydrogen. Experience should be exchanged between airports and with the industry, if possible by means of an institution.

Care for the most dangerous and the most likely situations must be taken by means of a detailed plan which is designed in cooperation with the relevant city and other authorities. This is usually required by environmental legislation anyway.

8.2. *Modular plant design*

The most likely accident is the release and dispersion of hydrogen gas. How to avoid this has already been discussed. If it happens, the extent of the spill must be limited by interrupting the connections between the plant parts, to the tanks, or between them, depending on where exactly the release happens. There must also be provisions for the emergency cut-off of the various pipeline segments and the tank positions, as well as other comparable elements. Even the whole liquefier plant should have the possibility to interrupt the connection to the airfield in order to prevent undesirable effects in either direction.

8.3. *Recognition of leaks and fires*

Hydrogen has neither colour nor odour. A hydrogen flame radiates mainly in near UV light, which means that it is almost invisible. This is a safety problem because an escape or, more seriously, a fire must be recognized as quickly as possible. Gas alarms at suitable places (in buildings and under roofs) have been mentioned already.

Gases can be mixed with an odorizing agent or one that gives a characteristic colour to the flame. This cannot be done at 20 K because all additives would solidify, get into the tanks, and interfere with the valves and pumps. More suitable would be paints and covers for pipes and tanks which change colour when heated. Such systems have been proposed for acetylene cylinders to make the progress of a decay visible.

Alternatively, paints could be used which react with hydrogen in a harmless, but characteristic way or which catalyze such a reaction. The advantage would be that the escape of gas could be detected sooner, independent of an ignition.

The airport could be controlled automatically for hydrogen fires by an optical device located on the roof of the tower or another suitable place. The characteristic combination of the spectral emission of hydrogen with the flame temperature should make it easy to distinguish such a flame from e.g. a hot engine.

8.4. *Fire*

Escaped hydrogen is easily ignitable. All vent and relief lines should, therefore, be equipped with a flame arrestor if there is a chance that a flame may enter them and cause

damage somewhere in the system. This may not be necessary as long as a sufficient amount of hydrogen flows through the line. However, an open safety valve vent line for example is normally not used, or only occasionally, and will contain oxygen. All lines from which hydrogen might be released should be arranged in such a way that the gas discharge will not create new risks. Weather conditions must be taken into account.

The extended use of hydrogen fire extinction devices is unsuitable. The best method is to interrupt the hydrogen supply to the flame by means of the modular design mentioned earlier and to let the gas in the line burn off. If only the flame is extinguished without interrupting the gas supply, gas can escape without burning, and the resulting ignitable cloud may be a greater danger than the flame.

9. AIRCRAFT DESIGN

9.1. *Amount and phase of hydrogen on board*

Design studies in the scope of the Cryoplane project are based on a modification of the twin-engined Airbus A310. A range comparable to that of a kerosene aircraft is achieved by a fuel supply of about 15 t or 200 m^3 LH_2. The fuel consumption will be between 1700 g/s (24 l/s) LH_2 during take-off and 530 g/s (7.5 l/s) in cruise [11].

The proposal has been discussed to use hydrogen slush (a mixture of liquid and solid) instead of the liquid. The tanks would be smaller and hold the fuel for a longer time in the liquid condition. However, the pressure in the tanks would be subatmospheric because slush exists only at the triple point, which has an absolute pressure of 7000 Pa in the case of hydrogen; this would facilitate air ingress into the tank and the lines in case of a leak. While slush with a solid content of up to 50 % is known to flow through tubes without problems, solid particles may interfere with valve or pump performance or support plugging at an elbow of the tube. Holding time is not the important thing anyway because the fuel of an aircraft will soon be consumed. The idea of using slush was, therefore, abandoned.

9.2. *Tanks, tank shape, tank distribution, and fuelling connections*

There are various reasons why the fuel should be distributed to more than one tank. The exact number and location of the tanks was discussed at length, but there was agreement about the arrangement of the tanks on top of the fuselage as shown in Figs 7–9 [11]. There will be an aerodynamic shroud so that the observer will just see a fuselage of somewhat uncommon height. The safety advantages of this concept will be discussed below.

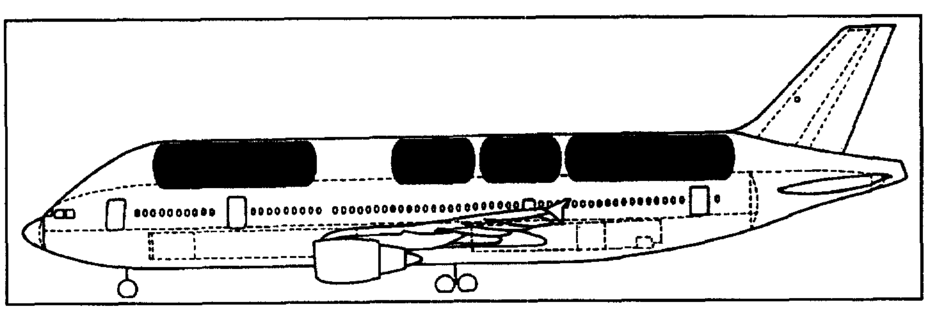

Fig. 7. Cryoplane tank arrangement, side view.

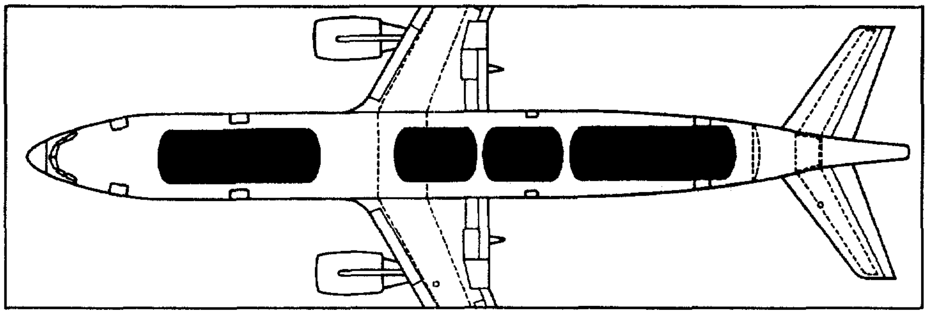

Fig. 8. Cryoplane tank arrangement, top view.

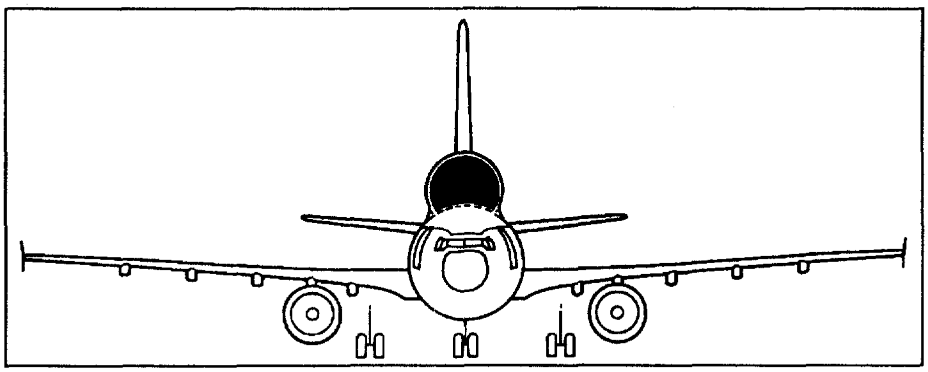

Fig. 9. Cryoplane tank arrangement, front view.

According to the present design status the fuel will be evenly distributed on two groups of tanks, consisting of a large and a small one each. This is the design presented in Figs 7–9. Since the large tank will have twice the volume of the small one, the small tank will accommodate about 2400 kg or 35 m^3 of LH_2. Each group will supply one engine in normal operation. The valve arrangement, however, allows also for other supply patterns.

The operating pressure of the tanks will be between 0.12 and 0.16 MPa with a nominal value of (0.14 ± 0.02) MPa. The test pressure will be 0.21 MPa and the burst pressure 0.32 MPa [11].

The tank shape is still under discussion. The circular cross section would principally be the best solution because it minimizes the tension in the tank wall and increases reliability and life expectancy. It is known both theoretically and from accident experience [5] that deviations from the circular shape favour material fatigue. Also discussed, however, is a crescent shaped tank with a lower profile, which would mean an aerodynamic advantage. Fig. 10 [11] compares both shapes. The behaviour after long service life cannot be judged on the basis of the present knowledge. Differences regarding safety aspects between both shapes are negligible.

The heat budget is affected by the fact that the liquid will slosh in certain flight situations (take-off, turns) and will make contact with warmer parts of the tank wall; this increases

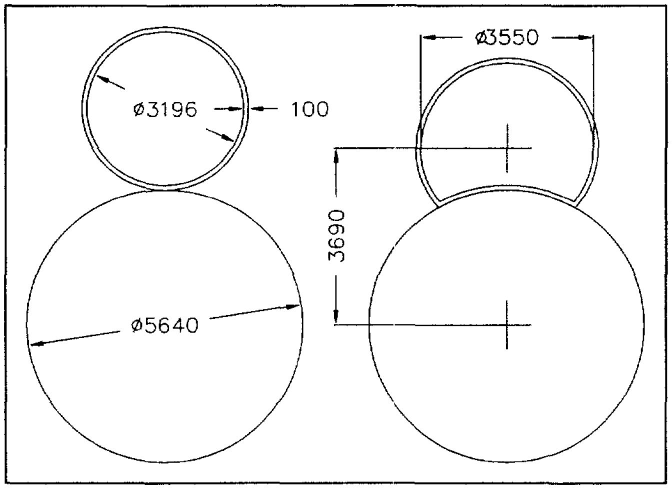

Fig. 10. Cryoplane fuselage with circular or crescent shaped tanks on top.

the vaporization rate. The temperature difference between tank top and liquid in a partly filled tank can be considerable because the gas is a poor heat conductor in comparison with the liquid.

10. AIRCRAFT RISKS

The in-flight risks to aircraft and passengers must be dealt with as far as possible by the design and by passive means because help from outside is not available. A high-risk component is the engine with its many fast moving parts. The breaking of a rotor blade in flight is dangerous because fragments may hit a tank or interrupt a fuel line.

One of the most important dangerous situations in flight, as well as for the airport, is the uncontrolled escape of hydrogen. This may be gas or liquid, and it may be a large outbreak as well as a stealthy escape. For the case of a release at high rates it should be checked which steering devices or similar components close to the leak might be affected. Damage can be done by mechanical impact, cooling and ice formation, or fracture due to loss of elasticity by cooling.

A crash landing is a dangerous situation with a certain probability. It should, of course, be avoided. But it is equally important to limit the potential damage in case it occurs. The greatest damage is frequently done not by the crash itself but in the later stages of the event.

11. PREVENTION OF FLIGHT ACCIDENTS

11.1. *Generally*

Statistical data about flight accidents show that only about 1/6 of accidents with known reasons are caused by deficiencies of the aircraft, while 2/3 are related to the crew [45]. The role of technical means in reducing this number can be to do routine work and permit the pilot to concentrate on the really important things. One step in this direction may be seen

in the fly-by-wire concept introduced recently. Such devices are particularly important with the new risks related to the Cryoplane in view.

Safe design and passive devices are the best means against in-flight problems. There is, however, not much experience with cryogenic systems with a very long operational life. This is a field which requires more research and development.

11.2. *Topics to be considered*

Safety relevant problems in connection with the design and operation of the tanks are for example:

- How does the liquid distribution vary during the flight? Which tank will be filled to which extent during which flight phase, and why?
- Which protection does the tank design offer against internal and external pressure, heat, or external force?
- Are the lines between tank and engine, the equipment, the safety devices, and the whole accessory suitable for their purpose? Who approves them, and on what basis?
- Is it meaningful to make the fuel lines from the tanks to the engines redundant?
- Which auxiliary and other devices are located near the tanks, and which means of operation, except hydrogen, are necessary for them?
- How tight and mechanically resistant is the separation between tank space and passenger compartment?

Some of these items will be discussed below, though final answers can generally not be given at this stage. They will depend not only on safety, but also on other technical and economical considerations.

11.3. *Materials*

All safety relevant data of the chosen materials of all components (including equipment) must be known for the whole range of operating temperatures. While this may not be a great problem for low-temperature steels, the situation is not always satisfactory for advanced materials for aircraft and spacecraft, for example, the aluminium–lithium alloy "Weldalite", which is one of the favourite aerospace materials. This is particularly true for the behaviour after long service life and under the influence of hydrogen. A Cryoplane, unlike a space rocket, will have to operate reliably for years.

Aluminium is of course not as heavy as steel, which explains its preferred use for aerospace purposes. While this may be an economical advantage for normal operation, there are also safety matters to be considered. Aluminium offers significantly less resistance against flames and heat than steel.

11.4. *Tanks*

Double-walled tanks with additional heat insulation have a certain mechanical stability anyway. How far they can resist to external force under specific conditions must be studied experimentally. Safe design of the tanks and their equipment are a key matter for the prevention of accidents.

Pressure vessels are designed according to the "leak before break" principle, which means that in case of a failure the vessel should not burst into fragments catastrophically, but rip open at one point and let the gas escape. The release is a bit slower, and protective measures can be taken. This principle should be used in aerospace applications as well.

Even in the absence of suspicious observations the presence of hydrogen in the tank space should always be assumed. Gas alarms should be there to alert the crew. Inertisation, at least partly, can be initiated automatically. The tank cover might be designed in such a way that ventilation is done in any case. This permits disposal of small amounts of gas without danger.

In case of insulation loss by an accident or handling error, the vaporization rate and the pressure in the tanks increase drastically. This means that, if the tanks are vacuum insulated, there should only be as many vacuum handling components as absolutely necessary, and they should not be accessible without special tools and procedures. Nobody should have a chance to tamper with it unless the aircraft is in a special maintenance facility. Similar precautions should be taken for any other type of insulation.

The mechanical load on the tank in normal operation is low and fairly constant. The thermal load, however, may oscillate considerably around the average value given by the temperature difference and the quality of the insulation. It is known [46] that vibration at a frequency of a few Hz enhances vaporization; whether this effect is also important for high frequencies (engine rotation) remains to be seen.

There will be a gap between the tanks in the rotation plane of the engine blades (see Fig. 7) to make sure that fragments do not hit a tank in case they break. What remains a risk in this case is a damage to the fuel lines. They must be suitably protected if their presence in this region cannot be avoided.

Safety relevant control and display devices should be separated from the tank to ensure their function in case of tank problems. Signal transmission to the crew should be as fail-safe as possible.

11.5. *Valves and equipment*

Experience with valve behaviour from ground and space operation cannot simply be adopted for aircraft service. Space missions are very short in comparison with the service life of an aircraft, and ordinary plants have other operating conditions than an aircraft. This means that a type test as well as an individual test of all components must be made with low temperature service for long periods in mind. Most plant failures due to technical reasons are caused by the failure or malfunction of some part of the equipment.

Type test programs of components should be done by a competent and independent organization like BAM or those which play a role in quality assurance systems according to ISO 9000 or EN 45000. One key element of the test sequence should be the simulation of the most unfavourable operational conditions, in particular rapid temperature changes. Another key element must be endurance tests under realistic conditions with a number of operational cycles depending on the expectations for service, combined with artificial ageing. Several samples or groups of samples should undergo the program in different sequences; BAM experience shows, for example, that it makes a great difference whether a valve is tested under high temperatures after a cold test or vice versa.

The principles outlined for valves hold for equipment and measuring devices of all types.

11.6. *Internal fuel transfer*

Transfer of cryogenic liquids should be avoided as far as possible for thermodynamic and safety reasons. Some common designs can or should not be used for a Cryoplane. Conventional aircraft redistribute the fuel during the flight between the tanks to improve the balance; some (like Airbus A310 ER) even use a tank in the tail fin for this purpose.

This is not useful for a Cryoplane because the transfer of LH_2 inevitably leads to losses, which would also be higher over long distances if the latter system was used.

Bubbles in the fuel lines should be avoided by all means because they affect the engine performance. Subcooling of the liquid (pressure rise above vapour pressure) by means of a pump has been proposed, but this question requires further research.

11.7. *Pumps*

The fuel transfer from the active tank to the engine is intended to be done by means of pumps. The same holds for the refilling of the active from the passive tank, while originally the use of overpressure was considered [11]. This, too, is a field for more development work. While there are proven fuel transfer systems in space service, their service life is usually rather short (about 10 min for a first stage, a few hours for a third stage). Satellite cryosystems with a long service life (between a few weeks and a year) avoid cryogen transfer completely and cool by contact or conduction. As far as liquid or gas must be transferred, passive systems are preferred which use the particular properties of the cryogen, as in the case of Helium II [47, 48].

Murphy's law tells us that pumps may and will fail; even their normal operation incurs thermal losses. This may make the transfer by means of pressure differences appear attractive, but this procedure is associated with losses of its own [49], as well as the liquid withdrawal under vapour pressure equilibrium. Pressure differences must be there before they can be used, and this requires auxiliary equipment (pumps, heat exchangers) which have risks of their own.

Suitable pump types or principles must be identified and optimized or developed. Centrifugal pumps have been proposed for the LH_2 transfer between the Cryoplane tank and the engines [11]. The key matter will be reliability for extended cryogenic service and protection against explosions. Three pumps are foreseen for each tank for redundancy reasons. Each individual pump should have a fail-safe design such that even in case of a failure it can be shut down without additional risks.

Most pumps comprise moving parts which give rise to friction problems; these are mainly unsettled for the environment discussed here. The matter is important, however, both for normal operation and for failure. More intensive tribological investigations of important material combinations are therefore necessary.

11.8. *Piping*

While the tanks will have an elaborate thermal insulation, the insulation for fuel lines may be of lower quality because the liquid will not remain in them for long. This reason, however, does not necessarily apply to the internal connections between the tanks. Double-walled lines with vacuum and superinsulation have safety advantages because they offer a higher mechanical stability. Monitoring of the insulation vacuum permits continuous leak control of tubes and connections and automatic initiation of countermeasures in case of a failure. These measures could be taken completely passively by making use of the pressure differences in the system or their disappearance (there are systems like this for flexible LPG hoses). Undetected leakage plays an important role in accidents [50]. While the control for leaks will mainly be done by gas detectors, there may be some isolated and gas-tight compartments where pressure sensors could do the same job.

The fuel lines in the wings and the interface between fuselage and wings are particularly

vulnerable in case of damage from outside. Care must be taken when the exact location of the fuel lines in this area is considered.

11.9. *Fuelling and other connections*

Fuelling of the aircraft provides a certain risk, as experience from spacecraft shows [51]. Mistakes may and will occur. They should be prevented by suitable training of personnel and by constructive measures. Connecting and disconnecting the fuel line to the aircraft should be easy, and hydrogen flow must be impossible unless the connection is in its correct state. The construction of the connections should be such that helium purging is not necessary, because (unlike hydrogen) helium is a resource of limited supply; such systems exist for surface vehicles [52]. The potential for human failure must be reduced wherever possible by the use of automatic and, if possible, passive systems.

While make-and-break connections are of course necessary for fuelling purposes, they are generally a risk and should be avoided wherever possible in favour of welded or other static connections. These, too, are weak spots, and their number should be minimized. This requirement is already contained in the general ideas for safe aircraft design.

11.10. *Operation*

Since most accidents happen due to human error, the safety level can be improved when errors can be avoided by technical means or suitable operation procedures. While safety is a key matter in aviation anyway, additional care must be taken in the case of Cryoplane to avoid the unwanted occurrence of flammable hydrogen/air mixtures. The start and shut-down procedures for the engines require special attention because an ignition is part of their normal operation. Hydrogen should have no chance to leave the fuel line prematurely, or it should at least be introduced into an inertized space.

Routine maintenance should be possible while the tank is cold. The filling of even a cold tank with cryogenic liquids requires a lot of time, as is known from motorcars [37], otherwise losses are incurred. Optimized quick and safe procedures must be developed. While LH_2 tank couplings are principally state of the art (Johnston couplings), they must be improved for higher flow rates.

12. FLIGHT EMERGENCY MEASURES

12.1. *Emergency situations*

In-flight problems may be uncomplicated such that they can be dealt with by the means available on board and the flight can be completed normally; maintenance or repair can be done later. Others may affect the safety of the aircraft; in this case the pilot will usually try to land on the nearest airfield.

A crash landing is possible if the handling of the aircraft is affected. Most crash landings happen on or near airports so that the fire brigade can help. The same holds for most other problems, because about 21 % of all incidents occur during the final approach and 27 % during landing [45].

Hydrogen is by its very nature safer than LNG or kerosene [25]. Unlike these, it does not create pools around the crash site which remain there for a long time, catch fire and prevent escape or help. Neither does hydrogen form flammable clouds which creep on the ground around the aircraft. Hydrogen disappears quickly because of its low density, as experience by BAM [21] and elsewhere has shown repeatedly. The formation of great clouds

is unlikely because it ignites easily. Hydrogen burns quickly under low heat emission, as it has been shown earlier.

12.2. *Tanks*

An aircraft with the tanks on top of the fuselage is safer than a conventional one because the tanks do not have ground contact at once if the gear is up during landing. The loss of a wing does not necessarily mean the loss or destruction of a tank.

The tanks might be fastened on the fuselage in such a way that they can be dropped when necessary; the cover must not obstruct such a process. The break points in the lines between the tanks and to the engines must be planned carefully, also the release procedure. An automatic release is not recommended because such provisions may work when they should not or vice versa, in particular under uncommon conditions like in an accident (see the recent accident of a Lufthansa Airbus at Warsaw). The tank must be deployed far enough from the aircraft without jeopardizing it.

12.3. *Valves*

The loss of an engine will leave the fuel lines wide open. Passive excess flow valves are recommended for this purpose to interrupt the flow from the tanks. This would also help if a wing is lost during a crash landing after a collision with an obstacle. While these devices are not completely tight, they are at least able to restrict the fuel loss until the complete interruption of the affected line can be done by the crew.

Safety valves must be type tested for their reliability at low temperatures. A critical point is their prompt release after not having been used for a long time, because they have a tendency to stick. Equally important is their closing after the release of large amounts of cold gas. These problems are common to all types of cryogenic installations.

Burst disks can be used alternatively to safety valves in certain places. They are tighter than valves, but cannot be closed again. They must be chosen under the aspect that the burst pressure must remain the same at all operating temperatures. Some applications use a combination of safety valve and burst disk.

12.4. *Piping*

A suitable arrangement of lines and equipment can prevent many dangerous situations from the very beginning. There should be provisions to isolate important pipe segments from the rest, similar to the modular concept of the airport plant. This may be useful not only for a massive hydrogen loss, but also for a discharge at small rates, because cutting off the damaged element from the tanks would give the crew more time to land the aircraft safely.

12.5. *Gas venting*

Gas which is discharged by a safety valve or a burst disk should be vented without creating additional dangers by the flow of discharged gas. Small amounts could be collected in a special tanks, but provisions for venting outside must exist.

Reference [12] and other studies propose a venting line which ends at the highest point of the aircraft in the tail fin. This is the logical position. The presence of oxygen there requires special attention to prevent its ingress into the hydrogen system. This can be done by back pressure valves which discharge hydrogen only when it is under a certain minimum pressure.

Venting of hydrogen into air creates an ignitable mixture. The ignition risk can be reduced by suitable design of the opening of the vent gas line, for example by reducing the speed of the gas flow. A flame arrestor should be provided by any means.

12.6. *Fire*

Fuel fires after a crash are an important risk. Statistical data [45] show that between 10 and 20 % of accident victims die in a fire after they have survived a crash or collision. Substances other than the fuel, like the tank insulation, can also burn and generate dangerous gases or smoke. If such dangers cannot be avoided at all by suitable choice of materials, passengers should at least have a chance for escape before being exposed to them.

The interface between the passenger compartment and tank space plays an important role in the protection from a hydrogen fire. Suitable design does not necessarily mean that it must be heavy; it might be provided with a protective paint which reacts endothermally in case of a fire. Such paints are state of the art for LPG tanks, and their performance has been tested with positive results [53, 54]. They might prolong the escape chance of the passengers by a few precious minutes. A fire can, of course, start in the passenger cell as well and affect the tanks. The heat load may be lower, but the protection of the fuselage against heat will probably on a lower level on this side.

13. TOPICS REQUIRING FURTHER INVESTIGATION

13.1. *Effects of the airport plant size*

While gas liquefaction plants are state of the art, the dimension discussed here is certainly not. There will be technical problems which cannot be solved by simple extrapolation of present experience. Another important point is that certain components for the LH_2 distribution are not available at the present time, at least not in the dimensions required for this purpose.

Plant design will certainly benefit from the experience of space centres. While the data from Florida and Kourou is comparatively easy to get, this was very difficult for the USSR space program. The situation has improved considerably meanwhile, also due to the Russian contribution to Cryoplane.

13.2. *Release of large amounts of LH_2*

Accidents in a liquefaction plant of the size in question may involve the release of fairly large amounts of hydrogen, either liquid or gaseous. The behaviour of such amounts under instantaneous or continuous release rates is not completely clear because previous experiments dealt usually with much smaller amounts. The NASA experiments in 1980 [28, 29] used amounts up to 6 m^3 liquid with release times of 30 s or less. The Arthur D. Little experiments [27] involved no more than 19 m^3. The BAM experiments in 1994 [20, 21] released about 0.7 m^3 during 1 min. The discharge behaviour of large amounts and large rates of liquid and cold gas, pool formation, vaporization, gas mixture dispersion, and ignition effects should be investigated to a greater extent. Parameters should be weather and ground conditions and the location and nature of igniters. Not settled is the issue whether a suitably great free cloud can detonate. There is a lack of reproducible, well-documented observations.

These matters are even more important in connection with aircraft accidents. While 240 m^3 or 17 t are not much in comparison to the plant inventory, it is much more than in

known experiments. There is a greater release risk in crashes and collisions, and more people can be affected.

While the effects from releases at smaller rates have been investigated before, the influence of buildings or industrial installations on the dispersion tends to make predictions difficult.

13.3. *Materials*

The behaviour of materials and components under the combined effect of cyclic pressure load and hydrogen is an important topic. Cyclic loads with low frequency are not well investigated. Nobody knows whether the phenomena occurring then are qualitatively different from those at higher frequencies which are common in laboratory tests. Also important is the resonance behaviour of the tanks and the other components.

It goes without saying that all material properties must be known for the whole range of temperatures. This is not always the case at this time, particularly for some interesting aluminium alloys.

13.4. *Storage tank performance*

The tank performance must be investigated comprehensively. This is of particular importance when they are to be built in great numbers. Tests should include simulations of the normal operation, in particular with a view on material fatigue under cyclic load and unfavourable combinations of operational conditions and their changes. Another matter is the risk associated with the tanks in plant accidents. Damaging the tanks by means of fire or blunt force (car crash) is possible. The filling level is an important parameter. Such experiments have so far mainly been made with motorcar tanks with a volume of about 120 l.

13.5. *Components and equipment*

There is a necessity to investigate connections, equipment, safety devices, control devices, and so on for reliability in extended service in connection with hydrogen. Experience of BAM or other test institutes is of limited value because "low temperature" for pressure vessel valves usually means $-20^\circ C$. A catalogue of requirements and a test program must be agreed upon at first. They can be improved on the basis of sample tests.

What is true for valves holds also for pipes and connections. Make-and-break connections in particular merit special attention, also tank couplings because they are used several times per day on a regular basis.

13.6. *Air ingress in aircraft tanks*

It will be almost impossible to totally prevent the ingress of traces of air into the tanks when they are refilled. Since a Cryoplane may remain in service with cold tanks for up to 18 months with several tank procedures per day, even small amounts may accumulate considerably. Solid oxygen and liquid hydrogen are known to form a detonative mixture. Procedures and devices are necessary to avoid air ingress into the tanks as far as possible, and to find out whether solid oxygen is present in the tanks and to get rid of it.

13.7. *Aircraft tank burst*

An aircraft accident, in particular a crash landing, is not an event but a process. The severity of the whole accident depends not only on the individual stages but also on how

they interact with each other. The aircraft tank prototypes should undergo a test program comparable to the one for the airport storage tanks.

For Cryoplane purposes the effects of one damaged tank should be investigated first. Matters to be looked into include the effects on still intact tanks or embrittlement and fracture of parts, or leakage of flanges due to cooling. Also interesting is the effect of a hydrogen fire on still intact tanks with either working or damaged insulation and on pipes, connections, and equipment.

The comparison of the results with those for conventional aircrafts would show whether hydrogen is more or less likely to cause damage after a crash than kerosene.

13.8. *Large scale LH_2* release

Various questions related to the release of large amounts of LH_2, no matter whether instantaneous or continuous, should be resolved. "Large" would mean amounts of the order of 10 t (140 m^3), comparable to the amount on board of a Cryoplane. Extent and shape of the clouds, how fast they become stationary under constant release rate, and how fast they disperse after the release stops, are matters of interest.

The next step would be the ignition of the cloud and the measurement of the pressure wave and the heat radiation. This must be done under realistic conditions. The spill of fuels which are liquid at ambient temperatures may generate an aerosol cloud the ignition of which can have devastating consequences. This has not been observed for hydrogen and is not easy to imagine, but could be a subject for investigation.

For the purpose of accident effect assessment it is important to know whether escaping LH_2 will form pools on the ground, how great they can be, and how fast they vaporize. Experiments have mainly been done using LN_2 [18]; first LH_2 measurements were made during the recent BAM experiments [21]. Other systematic investigations for hydrogen do not exist, but will be made [55]. Parameters are the release rate, the nature of the ground, ground and air temperature, and other boundary conditions.

13.9. *Fire effects*

Experience shows that many victims of crash landings suffer not so much from the crash itself, but from subsequent fire. It would be worthwhile to study the effect of a fuel fire near the tanks on the fuselage. This must be done under realistic conditions. Comparative experiments with kerosene can be made.

13.10. *Ignition and combustion*

Lean hydrogen/air mixtures are more interesting for safety considerations than those with high concentration. Their deflagration/detonation behaviour is as yet not known to a satisfactory degree. This could be done in medium sized experiments, for example by igniting gas in a balloon. Balloon results, however, do not give comprehensive information about the ignition behaviour in long ducts, so that the latter will have to be performed also.

13.11. *Physiological effects*

Liquid hydrogen may drip down and affect the passengers if the fuselage and a tank break. It is not clear whether hydrogen can enter a still more or less intact fuselage and cause a dangerously low oxygen content of the air. This matter might be clarified in a large scale experiment. "Cold burns" may occur if the liquid does not vaporize quickly or if it is not rejected by the warm skin. Injury might be possible if it intrudes in collars or sleeves.

13.12. *Modelling*

Numeric methods can be used to predict the effects of a hydrogen release. Most present programs for the treatment of industrial accident situations are, however, not suitable for hydrogen because a gas with such a low density is difficult to treat mathematically. Most programs are for gases with a density greater than that of air or at least similar. This is a field for development, because hydrogen will become important.

The situation might be improved by the calibration of principally suitable programs by means of experimental results. The results of the recent BAM experiments on cloud dispersion [20, 21, 43] will be used for this purpose, as far as possible. Of particular practical interest is the dispersion in realistic environments, like streets or industrial plants. An alternative would be experiments with artificial obstacles like grids because they are better comparable with numerical results. Another process lending itself to numerical analysis is pool formation and behaviour. There are results from the recent BAM experiments [21], and more systematic studies will follow [18, 55].

Also numerically accessible are the effects of a gas cloud ignition. Most present programs do not deliver satisfactory results, however, because extent and shape of a cloud or plume are difficult to estimate for the reasons explained above. Another problem is to make an assumption on how much gas takes part in a reaction.

These problems could be treated by means of a number of standardized accident scenarios and comparison of the results among each other and with experiments.

14. SUMMARY AND OUTLOOK

This study cannot cover all safety matters related to the development of a hydrogen aircraft like Cryoplane. The latter's design process is anything but finished, to mention just one reason. The basic outlines, however, can be discussed and judged in the same way as in other applications of safety engineering such as the chemical industry, surface vehicles, and plants and devices of any kind. The experience gathered in tests and approval procedures under environmental legislation can also be used.

What has been done here is a discussion of the installations on the airport and on board of the aircraft. The most important risks were identified, and protective measures for design, operation, and emergency were considered.

The result is that the Cryoplane and its infrastructure are feasible from the point of view of safety. The risks are not greater than those associated with any other great industrial plant, some of them even smaller. They can be dealt with by means of measures which are state of the art already now. The safety of aviation would not be affected.

The really new thing is that the necessary installations would be much greater than all existing ones. It is likely, however, that hydrogen fuel will be introduced not only in aviation, but in the energy technology generally. The reasons (supply and environment) are the same as for aviation, and they are equally compelling. This means that there will soon be hydrogen plants of today unknown size, and this quite independent of aircraft development. The load of the work thus rests not only on the shoulders of the aviation industry.

While the safety problems associated with the Cryoplane are solvable, they should not be taken lightly. All parties who have an interest in the future and the progress of aviation must increase their research and development efforts, and they should look for ways to do at least some tasks jointly. As long as hydrogen technology is not yet generally approved

and accepted, their assets should be put to work together instead of wasting them in premature competition.

Results should be disseminated in a suitable form to help convince the public of the safety of hydrogen technology. This is a task in which both industry and state institutions can take part.

The real problems for the introduction of hydrogen in aviation and generally, are not technical in nature, but political and economical. The necessary investments may not be available in the near future, but may be more abundant in the distant future. The work done today on Cryoplane and other projects of the same direction is a valuable contribution to the future not only of aviation, but of our technical civilisation generally.

REFERENCES

1. Winter, C. J., Hydrogen Technologies for Future Aircraft, *Proceedings of the International Seminary of DLE*, Bonn, 15, 16 November 1990.
2. Pohl, H.-W. and Malychev, V. V., Hydrogen in future civil aviation, *Hydrogen Energy Progress X*, 1994, 1969–1978.
3. Kocer, K. and Veziroğlu T. N., Liquid hydrogen powered commercial aircraft, *Hydrogen Energy Progress X*, 1994, 2057–2066.
4. Quick, L. H., Megalopolis Airport Requirements, presented at the *3rd Annual Meeting of the American Institute of Aeronautics and Astronautics*, Boston.
5. Behrend, E., Jaenicke, B., Krafka, H. and Schmidtchen, U., Folgenschwere Explosion—Bericht über Ursachen and Hergang des Berstens eines Wasserstoffbehälters in Hanau, *TÜ Technische Überwachung*, 1993, **34**, 176–179, 225–229.
6. Jenkins, I., A Survey of Hydrogen Safety Experience and Incidents; with an Evaluation for Use on Aircraft, *Proceedings of the European Safety and Reliability Conference*, 1994.
7. Behrend, E., Schmidtchen, U. and Meyer, W., Permeation of Helium through Polymers at Low Temperatures, *Proceedings of the 12th International Cryogenic Engineering Conference*. Butterworth, GB, Guildford, 1988, pp. 437–441.
8. Schmidtchen, U., Gradt, T., Börner, H. and Behrend, E., Temperature behaviour of the permeation of helium through vespel and torlon, *Cryogenics*, 1994, **34**, 105–109.
9. Hord, J., *Is Hydrogen Safe?* NBS Technical Note 690, Boulder (Colorado, U.S.A.), October 1976.
10. Fenn, D. B., Acker, L. W. and Algranti, J. S., *Flight Operation of a Pump-Fed, Liquid-Hydrogen Fuel System*, NASA TM X-252, Cleveland (Ohio) U.S.A., April 1960.
11. Deutsche Aerospace Airbus GmbH: *Cryoplane—Deutsch–Russisches Gemeinschaftsprojekt zum Einsatz kryogener Treibstoffe in der zivilen Luftfahrt*, Feasibility Study 1990–1992, Hamburg, 1992.
12. Brewer, G. D. (Ed.), LH_2 Airport Requirements Study, NASA Contractor Report CR-2700, October 1976, Washington, U.S.A.
13. Boeing Preliminary Design Department, *An Exploratory Study To Determine the Integrated Technological Air Transportation System Ground Requirements of Liquid-Hydrogen-Fueled Subsonic, Long-Haul Civil Air Transports*, NASA Contractor Report CR-2699, September 1976, Washington, U.S.A.
14. Alder, H. P. (Ed.), *Hydrogen in Air Transportation—Feasibility Study for Zurich Airport, Switzerland*, Eidgenössisches Institut für Reaktorforschung, Report No. 600, CH-Würenlingen, September 1986.
15. Gretz, J., Baselt, J. P., Ullmann, O. and Wendt, H., The 100 MW Euro–Québec Hydro-Hydrogen Pilot Project, *Int. J. Hydrogen Energy*, 1990, **15**, 419–424.

16. Drolet, B., Gretz, J., Kluyskens, D., Sandmann, F. and Wurster, R., The Euro–Québec Hydro-Hydrogen Pilot Project (EQHHPP): Demonstration Phase, *Hydrogen Energy Progress X*, 1994, 23–46.
17. *Safety Guide for Hydrogen*, National Research Council of Canada, Hydrogen Safety Committee, 1897.
18. Bongartz, B., Dienhart, B., Marx, J., Stauch, B. and Verfondern, K., Selected aspects of a safety analysis in a hydrogen energy economy, *Hydrogen Progress X* (1994) 225–234.
19. *Transport und Umschlag von tiefgekühlt verflüssigtem Erdgas (LNG) und unter Druck sowie tiefgekühlt verflüssigten Kohlenwasserstoffen (LPG) mit Seeschiffen auf deutschen See-Schiffahrtstraß*en—Risikoabschätzung, Bundesministerium für Verkehr, Arbeitsgruppe des Beirates für die Beförderung gefährlicher Güter; Bonn, December 1984.
20. Schmidtchen, U. and Marinescu-Pasoi, L., Dispersion of hydrogen and propane gas clouds in residential areas, *Hydrogen Progress X*, 1994, 255–260.
21. Schmidtchen, U., Marinescu-Pasoi, L., Verfondern, K., Nickel, V., Sturm, B. and Dienhart, B., Simulated Accidental Spill of Cryogenic Hydrogen in a Residential Area, *Cryogenics*, 1994, **34**(ICEC 15 Suppl.), 401–404.
22. Rehm, W. and Jahn, W., *Beitrag zur Auswertung von Ballon-Experimenten zu den Ausbreitungsfunktionen von detonierenden Wasserstoff-Luft-Gemischen mit Anwendungsfällen*, Reports of Research Centre Jülich No. 2854, December, 1993.
23. Baker, W. E., Kulesz, J. J., Ricker, R. E., Westine, P. S., Parr, V. B., Vargas, L. M. and Mosley, P. K., *Workbook for Estimating Effects of Accidental Explosions in Propellant Ground Handling and Transport Systems*, NASA Contractor Report 3023, August, 1978.
24. Edeskuty, F. J., Safety of liquid hydrogen in air transportation, *International DFVLR Symposium: Hydrogen in Air Transportation*, Stuttgart, 1979.
25. Brewer, G. D., The relative crash safety of LH_2-fueled aircraft, *Hydrogen Energy Progress IV*, 1982, 1697–1715.
26. Rich, B. R., Lockheed CL-400 Liquid Hydrogen Fueled Mach 2.5 Reconnaissance Vehicle, presented at the Working Symposium of LH_2-Fueled Aircraft, NASA–Langley Research Centre, 15, 16 May 1973.
27. *Interim Report on an Investigation of Hazards Associated with Liquid Hydrogen Storage and Use*, Arthur D. Little Inc, 15 January 1959.
28. Witcofski, R. D., *Dispersion of Flammable Clouds Resulting from Large Spills of Liquid Hydrogen*, NASA Technical Memorandum 83131, May, 1981.
29. Witcofski, R. D. and Chirivella, J. E., Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills, *Int. J. Hydrogen Energy*, 1984, **9**, 425–435.
30. *Verordnung über Druckbehälter, Druckgasbehälter and Füllanlagen (Druckbehälterverordnung—DruckbehV)*.
31. *Verordnung über elektrische Anlagen in explosionsgefährdeten Räumen* (ElexV).
32. *Verordnung über Arbeitsstätten* (Arbeitsstättenverordnung—ArbStättV).
33. *Gesetz zum Schutz vor gefährlichen Stoffen* (Chemikaliengesetz—ChemG); *Verordnung über gefährliche Stoffe* (Gefahrstoffverordnung—GefStoffV).
34. *Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen and ähnliche Vorgänge* (Bundes-Immissionsschutzgesetz); *Zwölfte Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes* (Störfallverordnung).
35. Schmidtchen, U., Gradt, T., Würsig, G. and Meyer, W., Safe handling of large amounts of liquid hydrogen, *Cryogenics*, 1993, **3**, 813–817.
36. Schmidtchen, U. and Würsig, G., *Lagerung and Seetransport groß*er Mengen flüssigen

Wasserstoffs am Beispiel des Euro–Québec Hydro-Hydrogen Pilot Project—Überblick über die in Deutschland anzuwendenden Gesetze, Verordnungen and Technischen Regeln, BAM Research Report No. 195, Berlin, Wirtschaftsverlag NW, Bremerhafen, 1993.

37. Tachtler, J. and Szyszka, A., Car fueling with liquid hydrogen, *Linde Reports on Science and Technology*, 1993, **51**, 31–38.
38. Bracha, M., Lorenz, G., Patzelt, A. and Wanner, M., Large-scale hydrogen liquefaction in Germany, *Int. J. Hydrogen Energy*, 1994, **19**, 53–59.
39. Linde, Fa. (U.S.A.), *Survey Study of the Efficiency and Economics of Hydrogen Liquefaction*, NASA Contractor Report CR-132631, April, 1975.
40. Jones, L., Wuschke, C. and Fahidy, T. Z., Model of a cryogenic liquid-hydrogen pipeline for an airport ground distribution system, *Int. J. Hydrogen Energy*, 1983, **8**, 623–630.
41. *Gesetz über die Umweltverträglichkeitsprüfung (UVPG)*.
42. Ordin, P. M., *Review of Hydrogen Accidents and Incidents in NASA Operations*, NASA-TM X 71656, 26 August 1974.
43. Rastogi, A. K. and Marinescu-Pasoi, L., Numerical simulation of hydrogen dispersion in residential areas, *Hydrogen Energy Progress X*, 1994, 245–254.
44. *UVV Gase* (VBG 61).
45. Deutsche Aerospace Airbus, *Lufttüchtigkeit and deren Aufrechterhaltung*, GQ21-478/10/93.
46. Rotenberg, Y., Vibration enhanced boil-off rate from a cryogenic hydrogen tank, *Hydrogen Energy Progress VI*, 1986, 164–172.
47. Petrac, D. and Mason, P. V., Infrared Astronomical Satellite (IRAS) superfluid helium tank temperature control, *Adv. Cryog. Engng.*, 1984, **29**, 661–667.
48. Denner, H.-D., Klipping, G., Klipping, I., Lüders, K., Oestereich, T., Ruppert, U., Schmidtchen, U., Szücs, Z. and Walter, H., Improved active phase separator for helium II space cooling systems, *Adv. Cryog. Engng.*, 1982, **27**, 1079–1086.
49. Engel, J., Klipping, G. and Walter, H., Evaporation losses during handling of liquid helium, *Proceedings of the ICEC* 6, 1976.
50. Zalosh, R. and Short, T., *Comparative Analysis of Hydrogen Fire and Explosion Incidents*, Factory Mutual Research Corporation, Norwood, U.S.A., 28 February 1978.
51. Wybranowski, E., A 10,000-gpm liquid hydrogen transfer system for the Saturn/Apollo program, *Adv. Cryog. Engng.*, 1971, **17**, 147–155.
52. Hettinger, W., LH_2 Tankstelle für wasserstoffbetriebene Fahrzeuge, *DKV Tagungsbericht* 21 Vol. I p. 203–218.
53. Droste, B., Mallon, M. and Probst, U., Neuartige Brandschutzbeschichtungen für Flüssiggas-Lagertanks, *TÜ Technische Überwachung*, 1989, **30**, 166–172.
54. Droste, B., Die Bewertung der Sicherheit von Umschließungen zur Lagerung von Flüssiggas. In *Kolloquium über Fragen der Chemischen Sicherheitstechnik*, 5., ed. H. Steen. BAM, Berlin, 1990, 83–101.
55. Dienhart, B. (Research Centre Jülich), Thesis (in prep.).